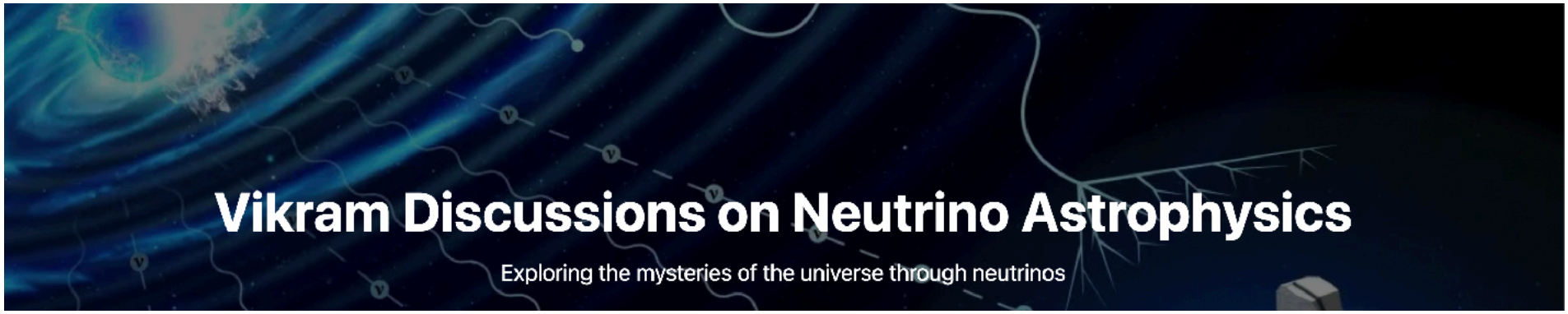


The KM3NeT event: what can we learn from a single neutrino?

Ranjan Laha

Centre for High Energy Physics

Indian Institute of Science, Bengaluru, India

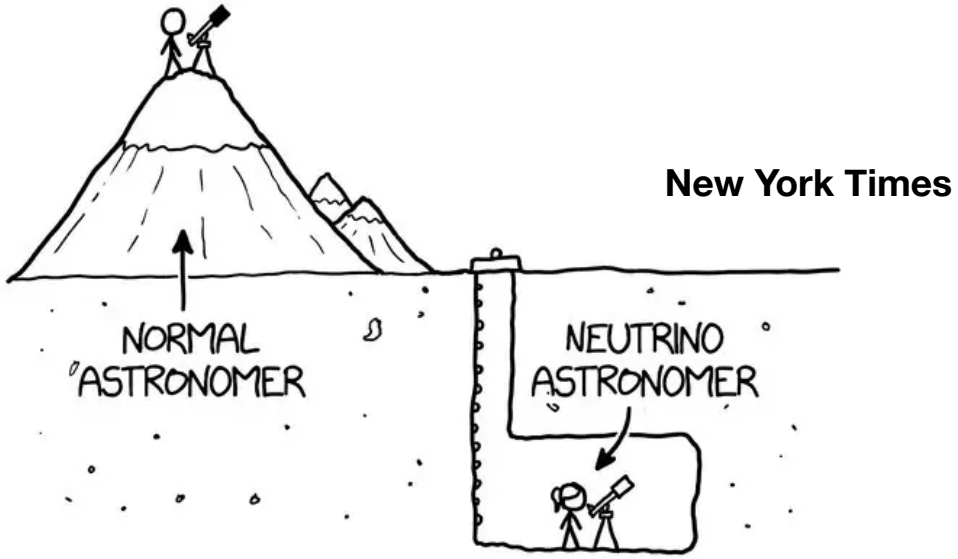
Thanks to my collaborators: Ranjini Mondol, Subhadip Bouri, and Akash Kumar Saha

Centre for High Energy Physics

Neutrino telescope concept

- First proposed by M. Markov at ICHEP conference, 1960: “ We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Cherenkov radiation”

credit: Subhadip Bouri



Contents

- High-energy neutrino astrophysics
- KM3NeT: km^3 neutrino telescope
- Beyond the Standard Model physics with KM3-230213A
- Conclusion

High-energy neutrino astrophysics

What are the sources of Cosmic Ray?

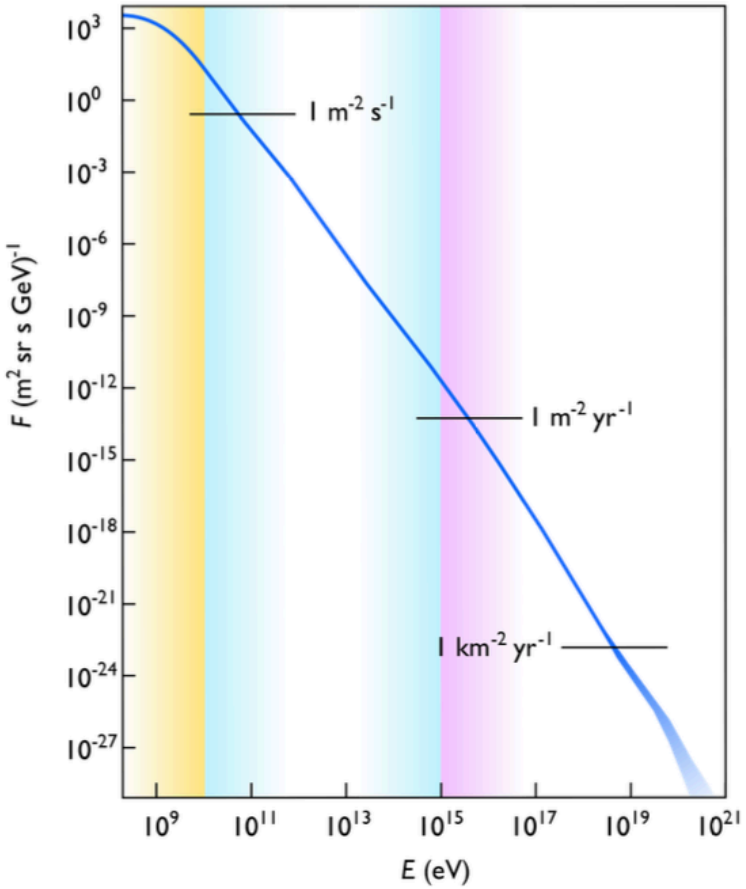


Fig: Cosmic flux versus particle energy at the top of Earth's atmosphere (credit: wikipedia)

What are the sources of the highest energy particles in our universe, the high-energy ($\geq 10^{15}$eV) cosmic rays ?

credit: Subhadip Bouri

Neutrinos and gamma rays, a partnership to explore the extreme universe

credit: Subhadip Bouri

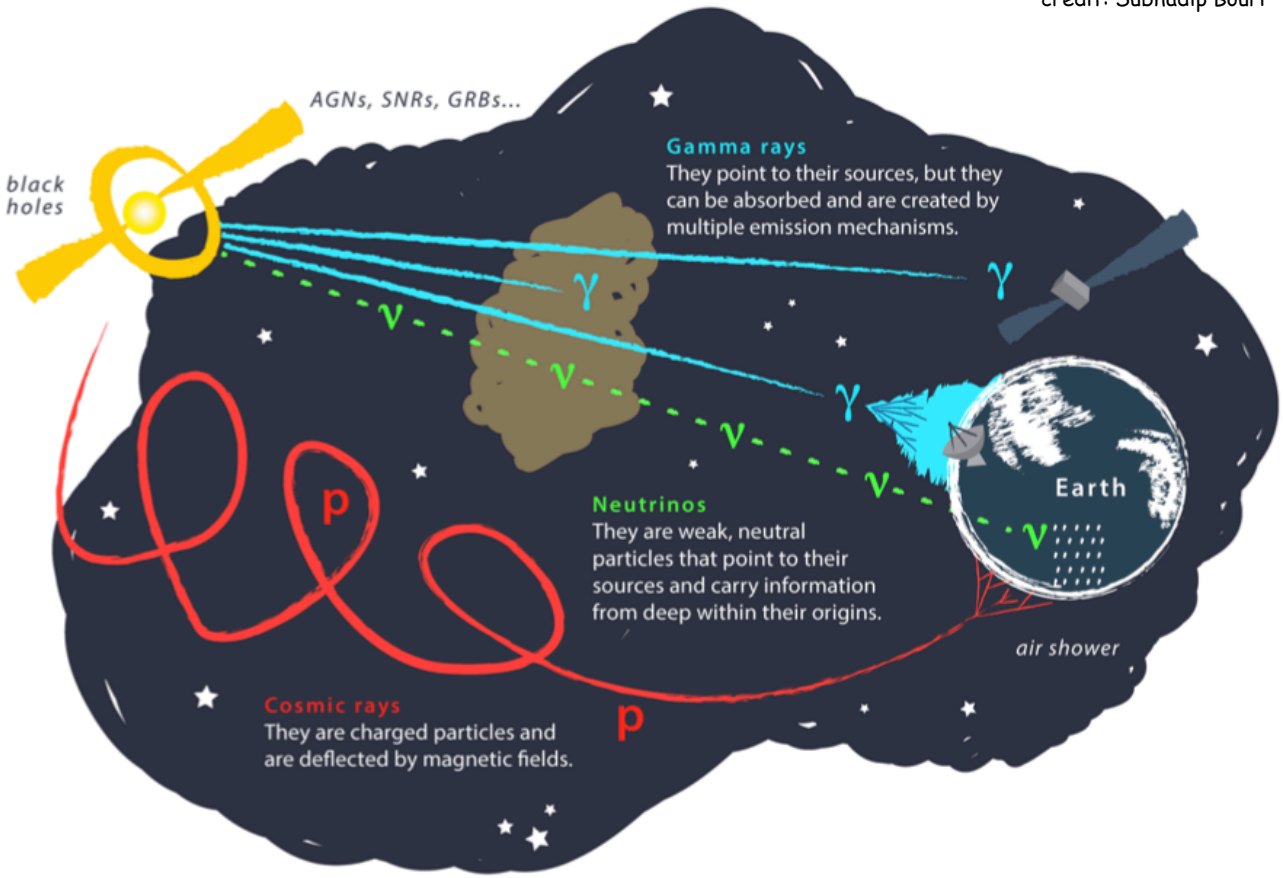


Image courtesy: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

High-energy neutrino production

$$p + p_{\rm target} \rightarrow n_\pi \left[\pi^+ + \pi^- + \pi^0\right] + X$$

$$p + \gamma_{\rm target} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, {\rm BR} = 2/3 \\ n + \pi^+, {\rm BR} = 1/3 \end{cases}$$

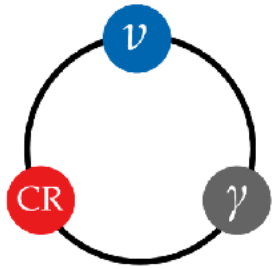
$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

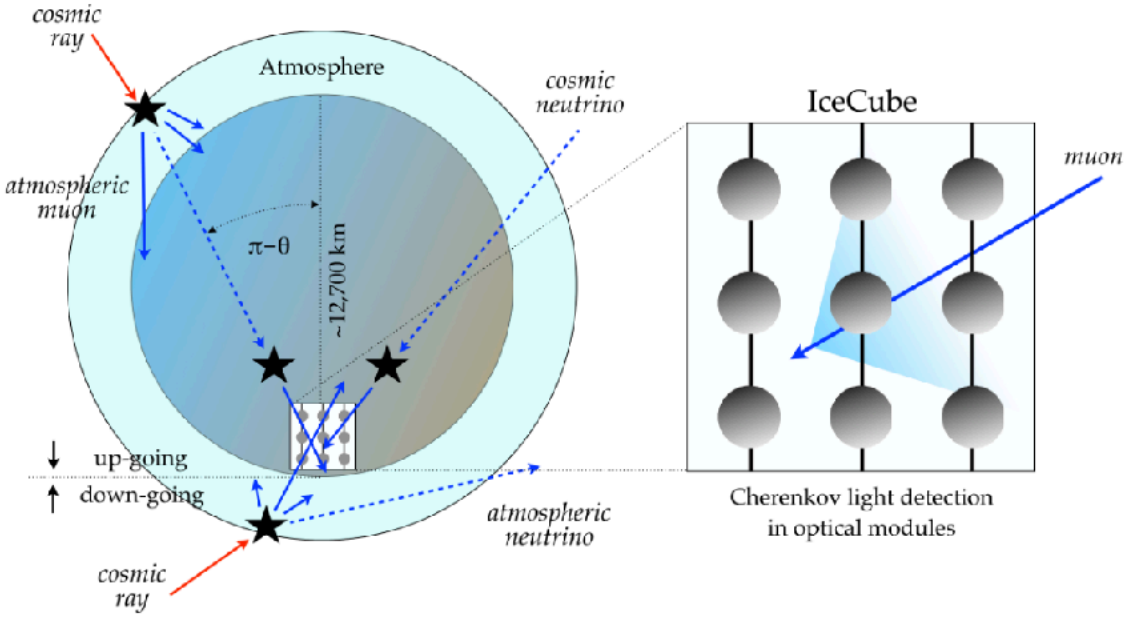
$$n\ ({\rm escapes}) \rightarrow p + e^- + \bar{\nu}_e$$

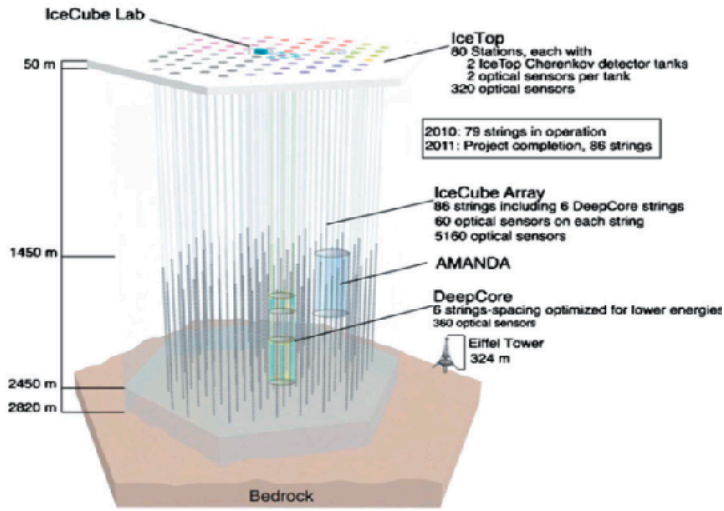
Neutrino energy ~ proton energy/20
Gamma-ray energy ~ proton energy/10

credit: Subhadip Bouri



How IceCube detects neutrinos?





courtesy:2202.00694

Courtesy: IceCube collaboration

$$\nu_l + \mathrm{N} \rightarrow l + hadrons \quad \text{(Charged Current interaction)}$$

$$\nu_l + N \rightarrow \nu_l + hadrons \quad \text{(Neutral Current interaction)}$$

Similar types of interactions happen for anti-neutrinos.

Current status of the high-energy astrophysical neutrino sources

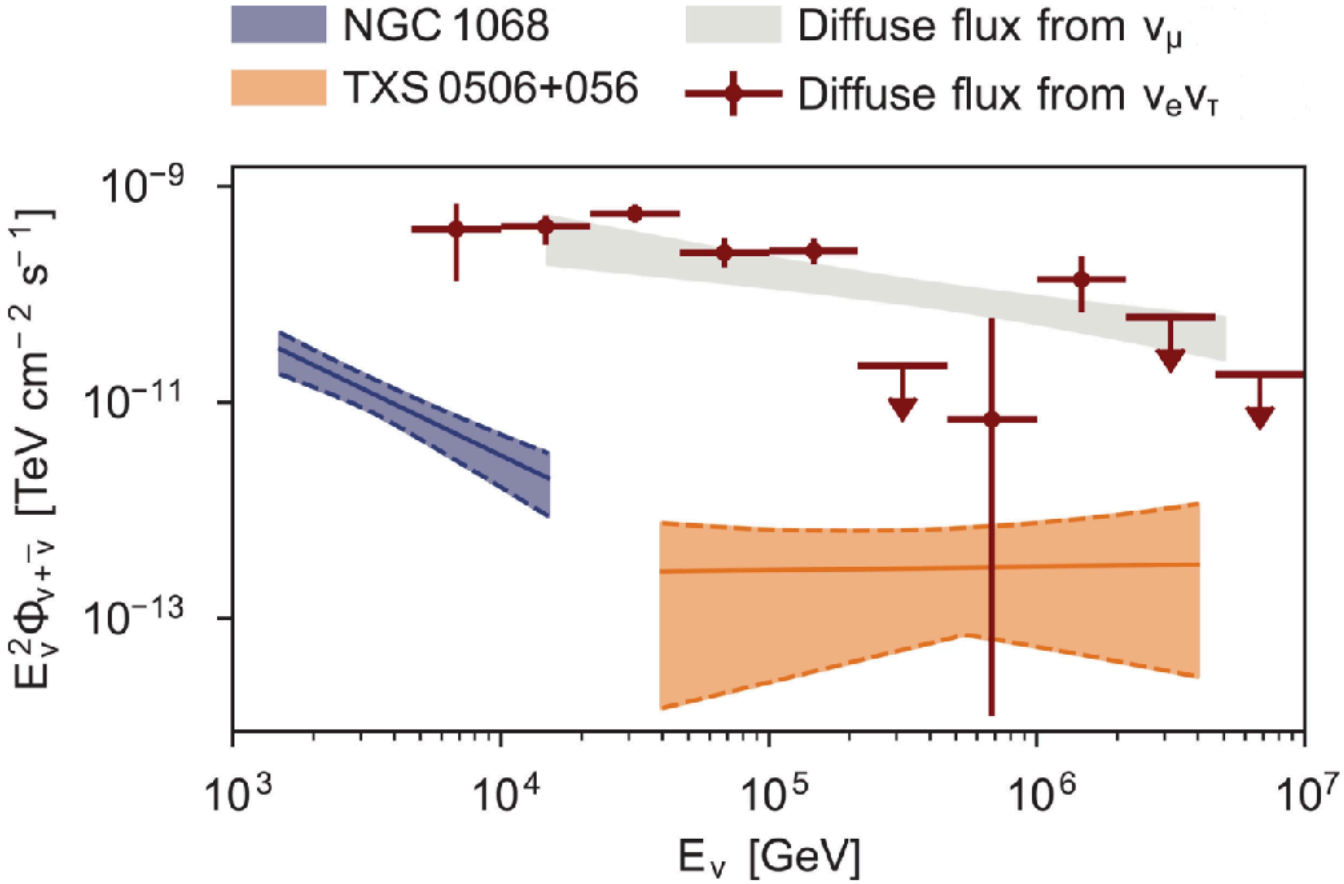


Fig: The high energy neutrino flux observed by IceCube. TXS 0506+056 and NGC 1068 are confirmed high-energy astrophysical neutrino sources till now. We also observe a high-energy diffuse astrophysical neutrino (in all flavors) flux. Currently, we do not know what sources contribute entirely to the high-energy diffuse astrophysical neutrino flux. [courtesy: 2211.09972]

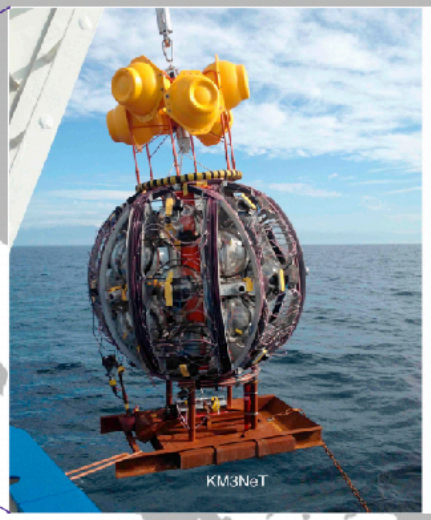
credit: Subhadip Bouri

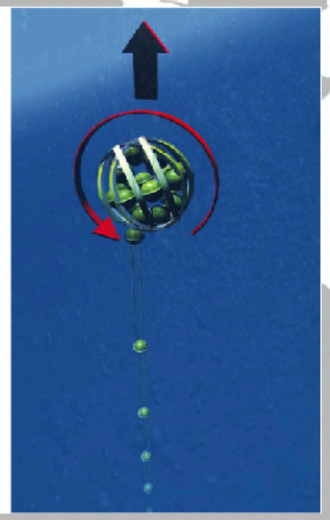
KM3NeT: km^3 Neutrino Telescope

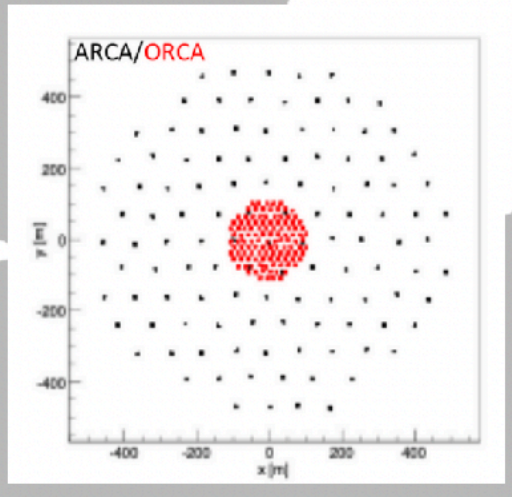
KM3NeT

KM3NeT/ORCA

ex ANTARES site







KM3NeT/ARCA

ORCA (spacing 23×9 m): **high statistics** of atmospheric ν

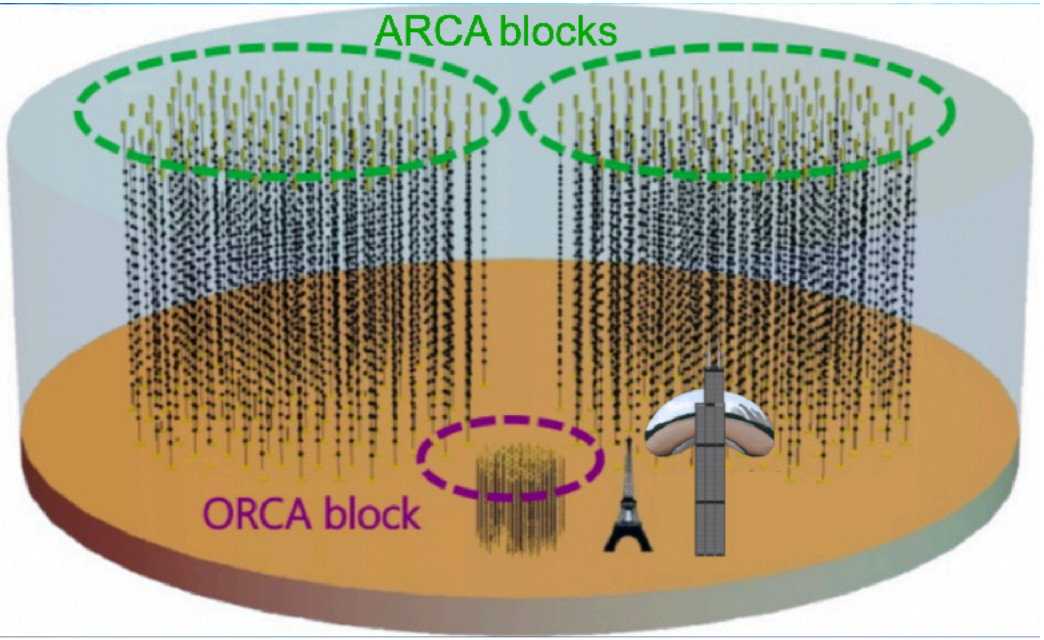
ARCA (spacing 90×36 m): **rare fluxes** of extraterrestrial ν

Gozzini PPC 2024

ORCA: Oscillation Research with Cosmics in the Abyss

ARCA: Astroparticle Research with Cosmics in the Abyss

KM3NeT ARCA and ORCA blocks



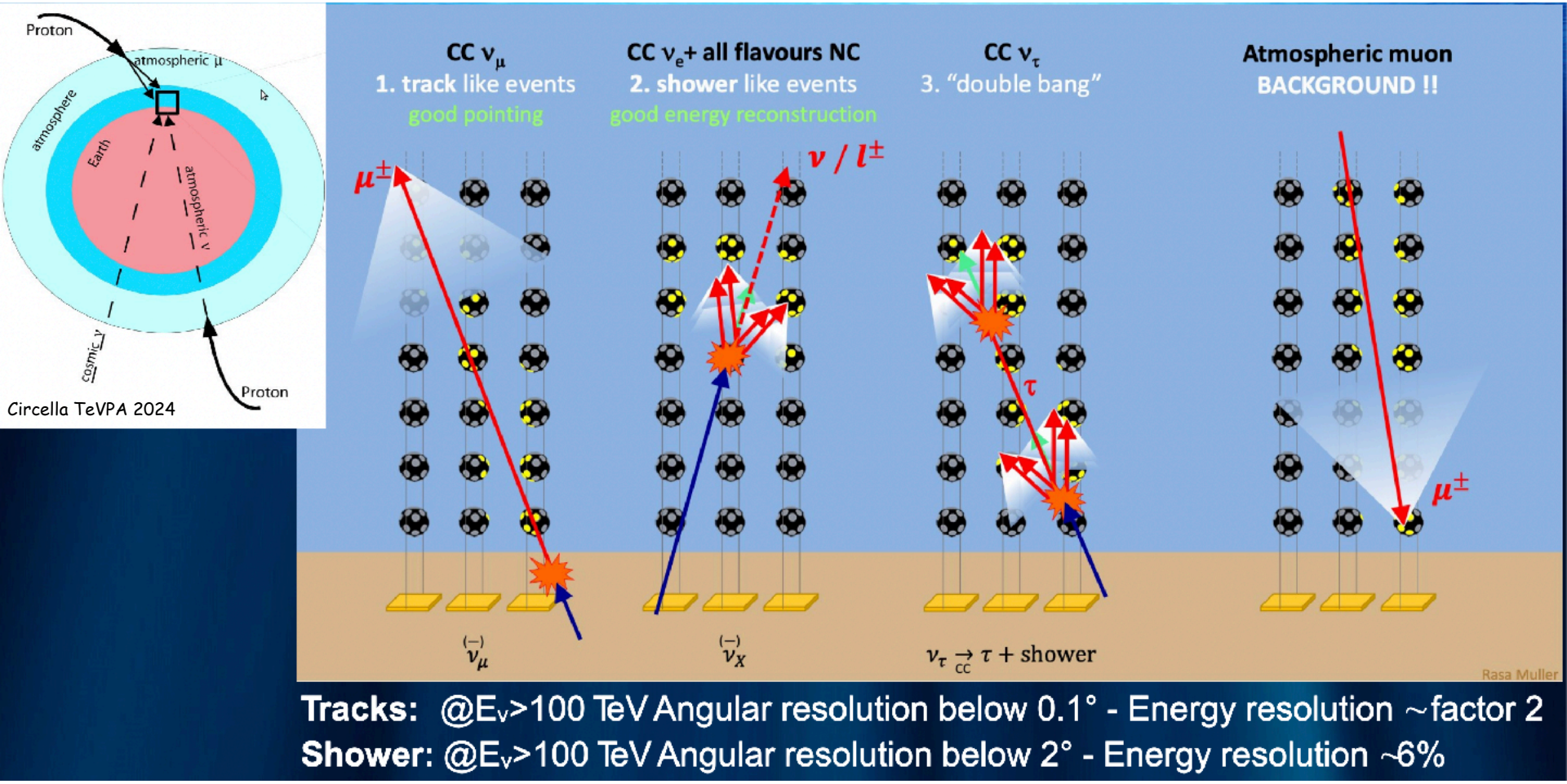
Circella TeVPA 2024

	ARCA	ORCA
Location	Sicily (IT)	Toulon (FR)
Depth	3450m	2450m
No. of DUs	2 x 115	115
DU horizontal spacing	90 m	20 m
DOM Vertical Spacing	36 m	9 m
DOMs/DU	18	18
PMTs/DOM	31	31
Instrumented water mass	1 Gton	7 Mton
DUs deployed	28	23

ORCA: Sensitive to neutrinos + anti-neutrinos in the energy range ~ 1 GeV to 100 GeV

ARCA: Sensitive to neutrinos + anti-neutrinos with energies beyond ~ 100 GeV

Neutrino detection technique in KM3NeT



KM3NeT can detect both neutrinos and anti-neutrinos of all flavours

THE RECORD NEUTRINO

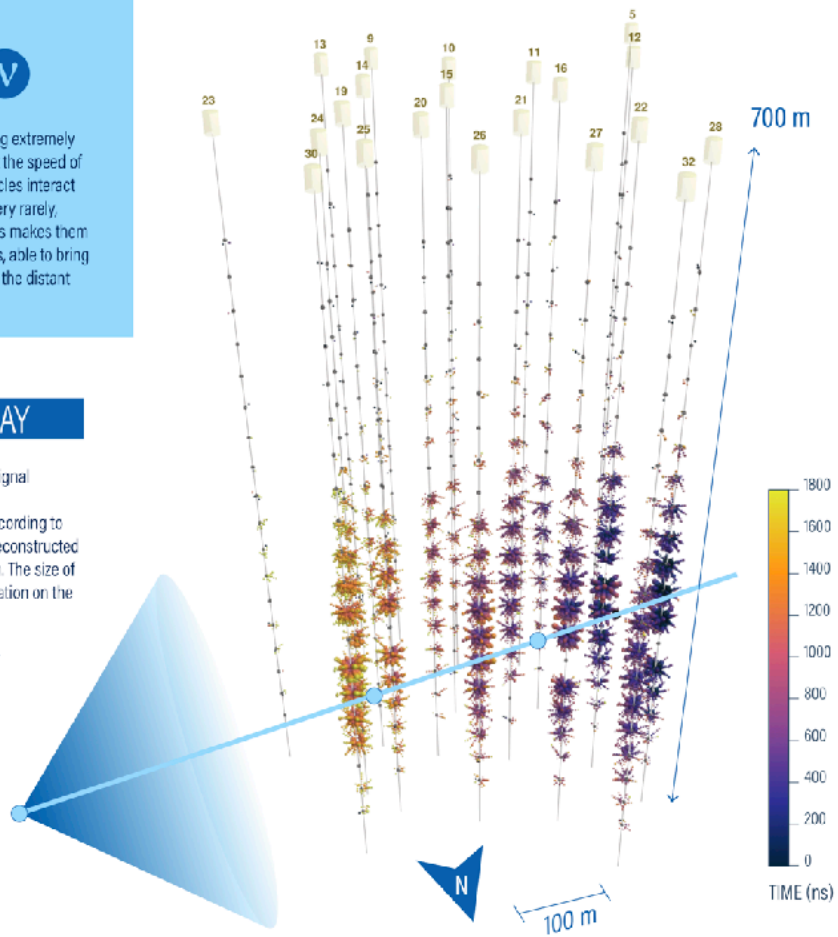
On 13 February 2023, at a depth of 3450 metres off the coast of Sicily, in Italy, the ARCA detector of the KM3NeT submarine neutrino telescope recorded an extraordinary signal: produced by a neutrino with a record energy of about 220 PeV, corresponding to 220 million billion electronvolts. This signal, named KM3-230213A, provides the first evidence that neutrinos with such extreme energies exist in the universe.

NEUTRINOS

With no electric charge, being extremely light and travelling almost at the speed of light, these elementary particles interact only weakly, and therefore very rarely, with matter. Their elusiveness makes them valuable cosmic messengers, able to bring us unique information about the distant universe.

THE EVENT DISPLAY

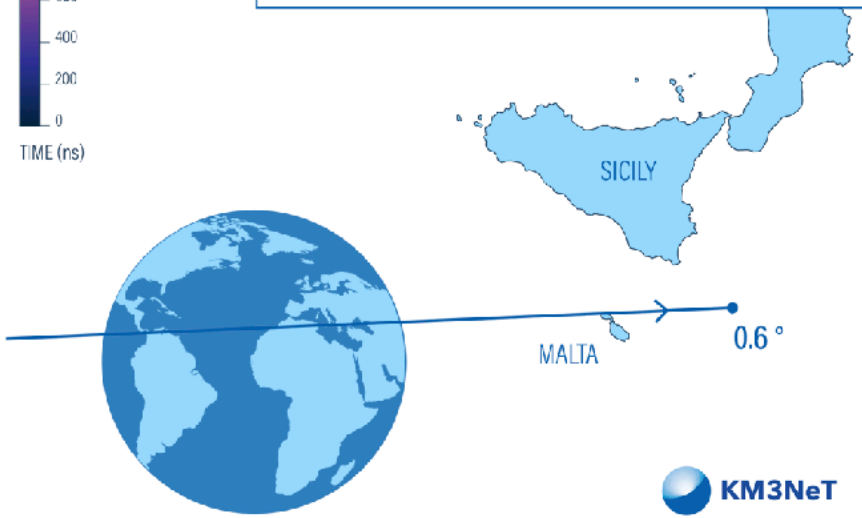
A view of the KM3-230213A signal detected by KM3NeT.
The spheres are coloured according to the detection time and the reconstructed track of the particle is shown. The size of the blue cone gives an indication on the amplitude of the signal.



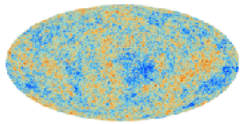
https://www.km3net.org/km3-230213a/the-signal/

KM3-230213A IDENTIKIT

The cosmic neutrino plunged into the Mediterranean Sea and crossed the Malta continental shelf with an inclination of 0.6° above the horizon. During this journey, it travelled almost at the speed of light and interacted with an atomic nucleus, generating an ultra-relativistic muon, which crossed the whole detector.



THE SOURCES



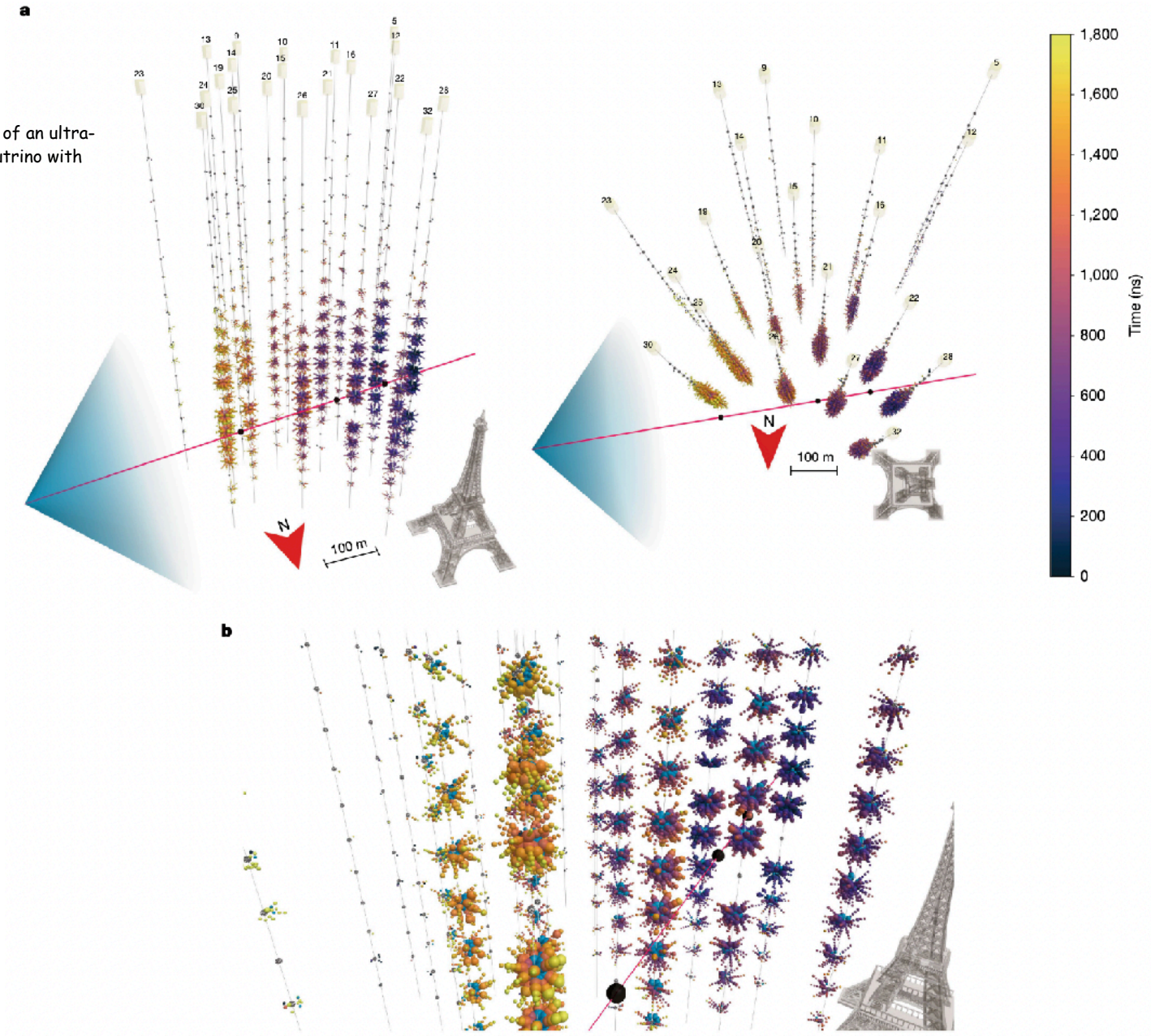
The origin of the ultra-high energy neutrino could have been one of the cataclysmic events that animate our universe, such as an active galactic nucleus or a gamma-ray burst. Or it could be a neutrino generated by the interaction of an ultra-high energy cosmic-ray particle with the cosmic background radiation that permeates the universe.

KM3NeT

Co-funded by the European Union

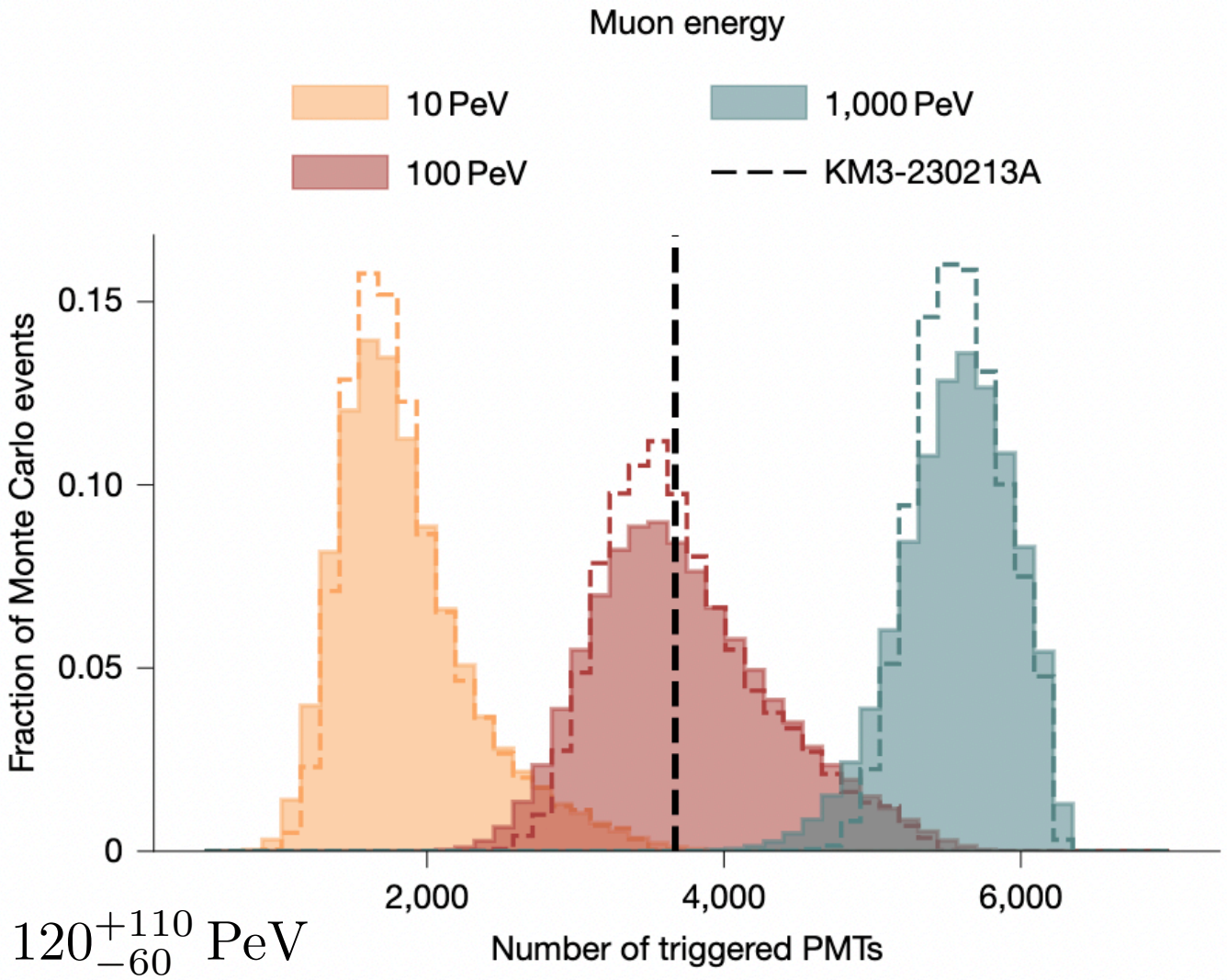
The record-breaking neutrino

KM3NeT "Observation of an ultra-high-energy cosmic neutrino with KM3NeT"



The record-breaking neutrino

KM3NeT "Observation of an ultra-high-energy cosmic neutrino with KM3NeT"

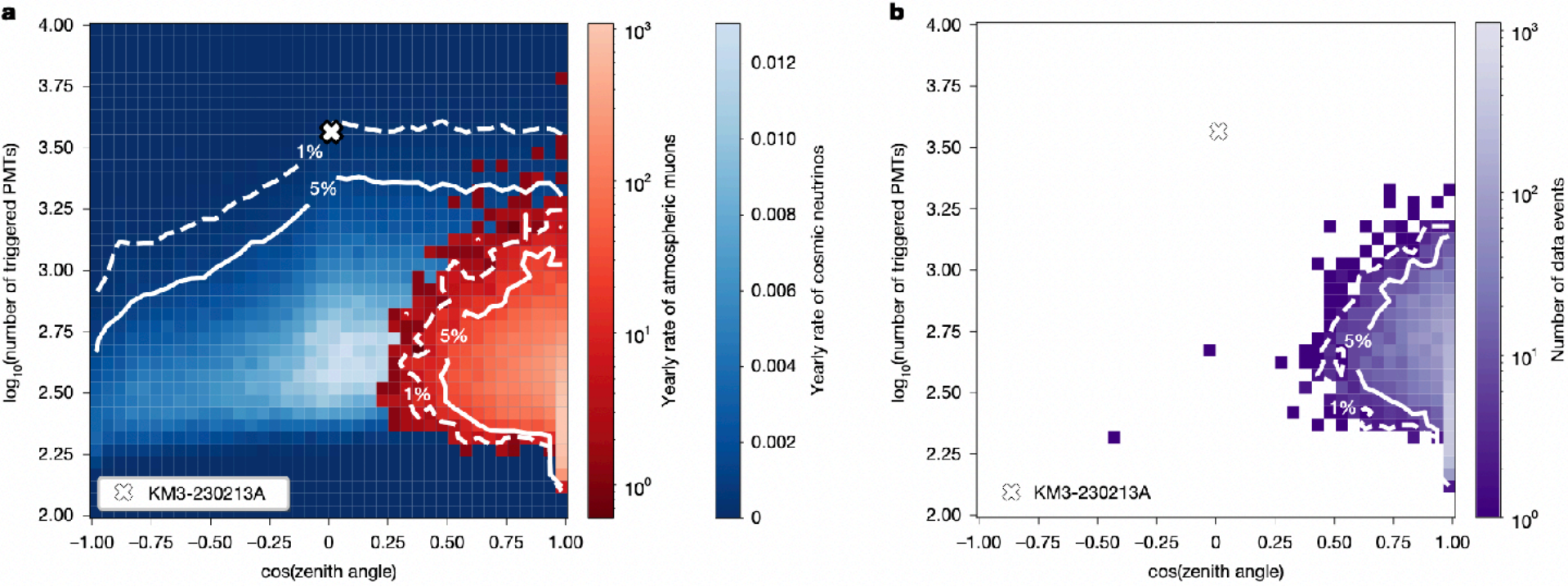


Deposited muon energy = 120^{+110}_{-60} PeV

Median muon neutrino energy producing such a muon in ARCA = 220 PeV

Energy range containing 90% of the incoming neutrino energies: 72 PeV − 2.6 EeV

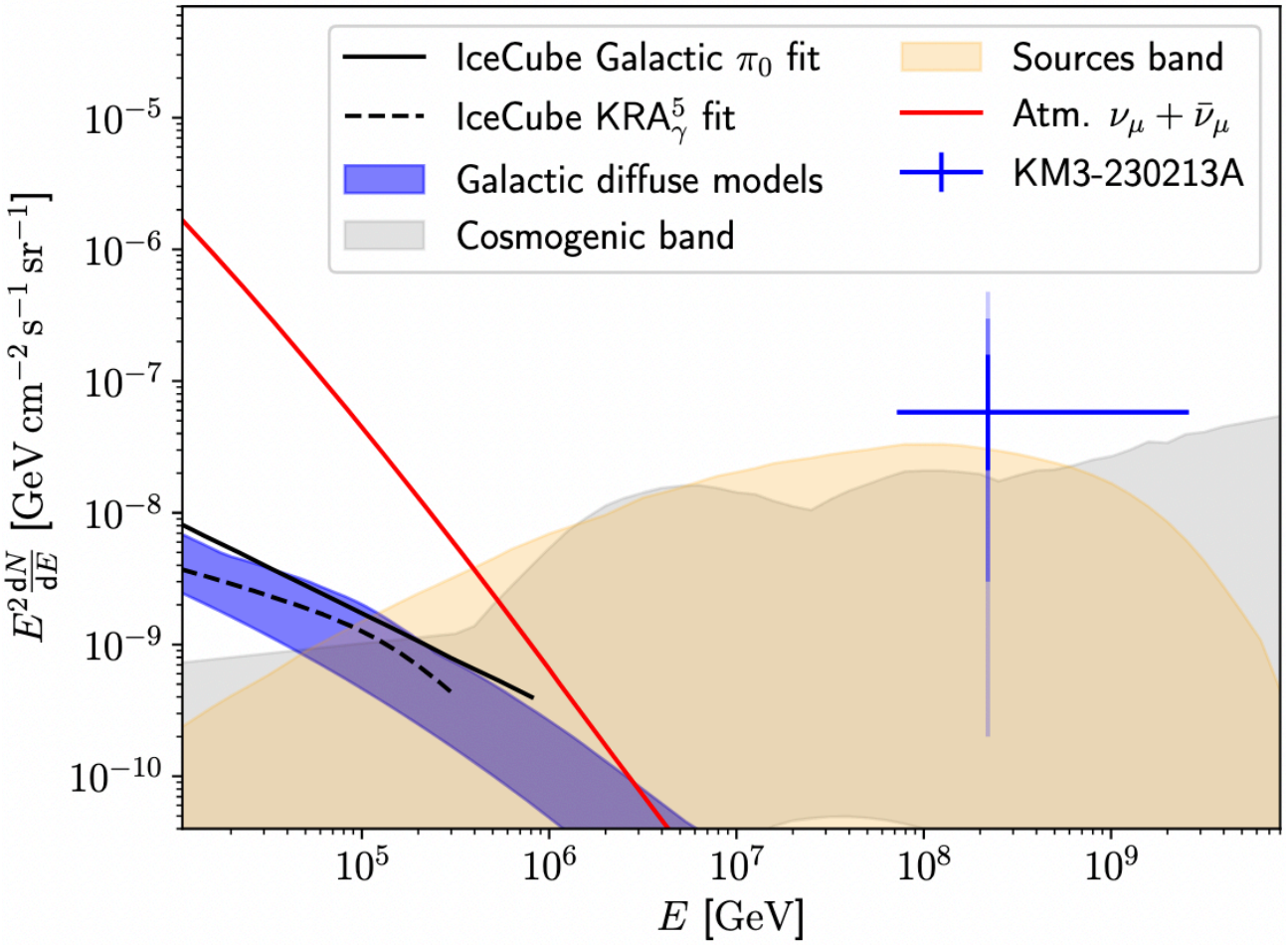
The record-breaking neutrino: definitely astrophysical



Extremely unlikely for this event to be due to a fluctuation of the atmospheric neutrino or muon background: comes from a region of the sky where atmospheric muons almost cannot come from

KM3NeT "Observation of an ultra-high-energy cosmic neutrino with KM3NeT"

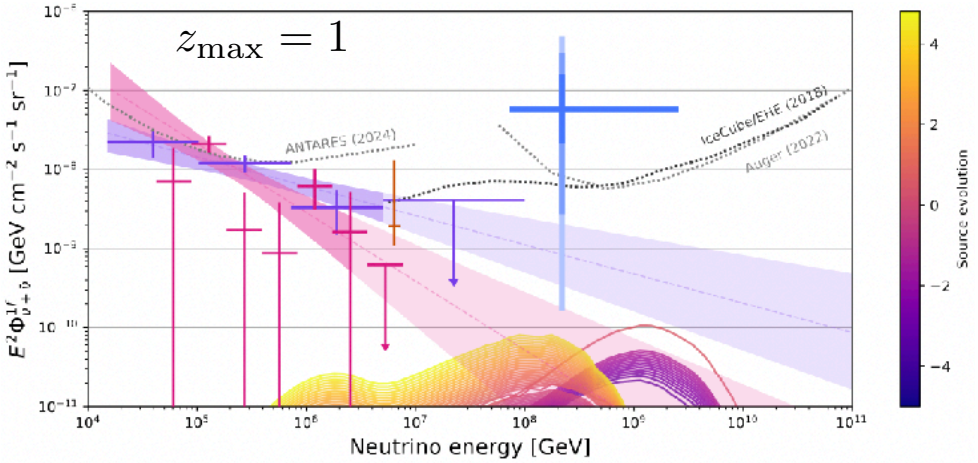
KM3-230213A: is it coming from our galaxy?

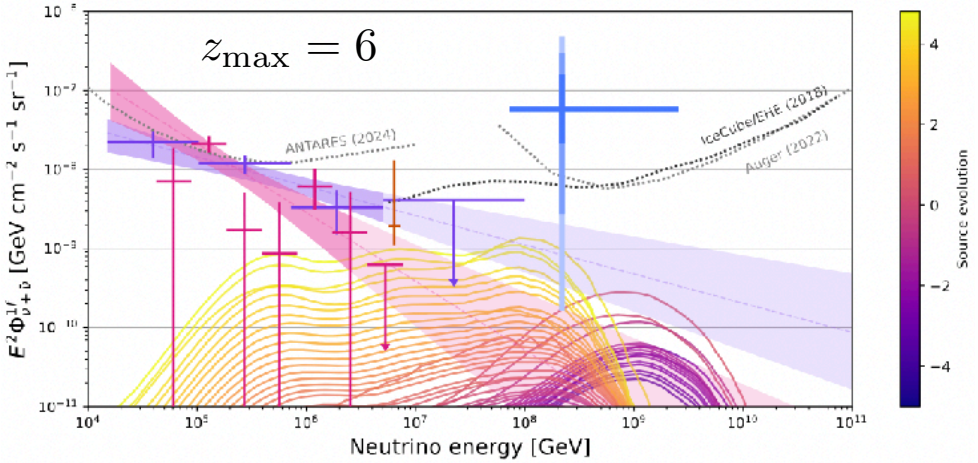


The event cannot come from the Galactic diffuse emission and is not in the direction of any Galactic high-energy source

KM3NeT "On the Potential Galactic Origin of the Ultra-High-Energy Event KM3-230213A"

KM3-230213A: is it of cosmogenic nature?



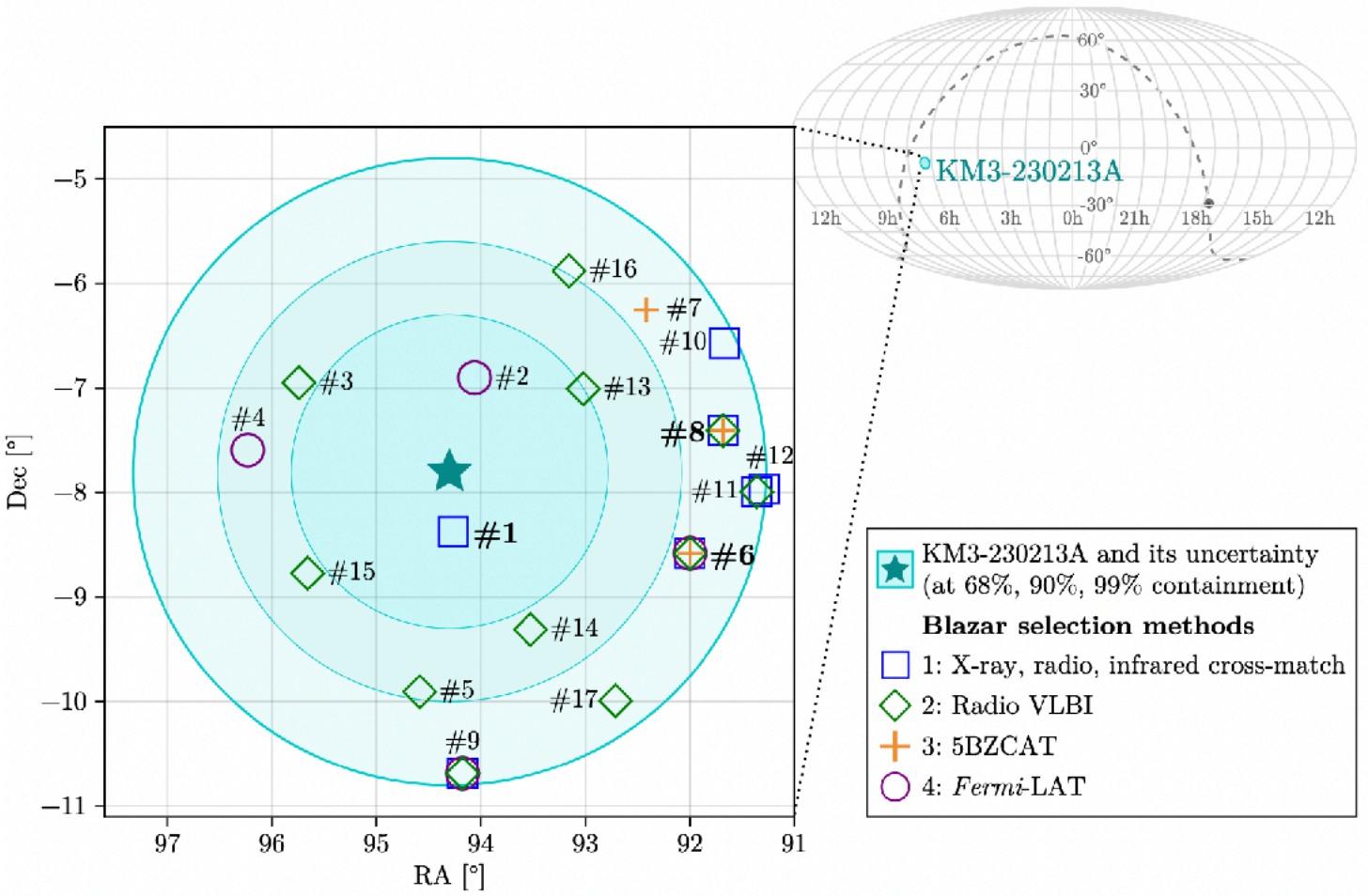


KM3NeT "On the potential cosmogenic origin of the ultra-high-energy event KM3-230213A"

The event may be in tension with the ultra-high-energy cosmic ray measurements. However, it can be reconciled if we do the redshift integral till z = 6 and assume a sub-dominant fraction of protons in the ultra-high-energy cosmic-ray flux

KM3-230213A: is it from a blazar?

KM3NeT Characterizing Candidate Blazar Counterparts of the Ultra-High-Energy Event KM3-230213A"



About 17 blazars are in a region about 3^0 from the best-fit direction of the event

Two sources with known black hole masses and red-shifts: PMN J0609-0615 and PKS 0605-085

Beyond the Standard Model physics with KM3-230213A

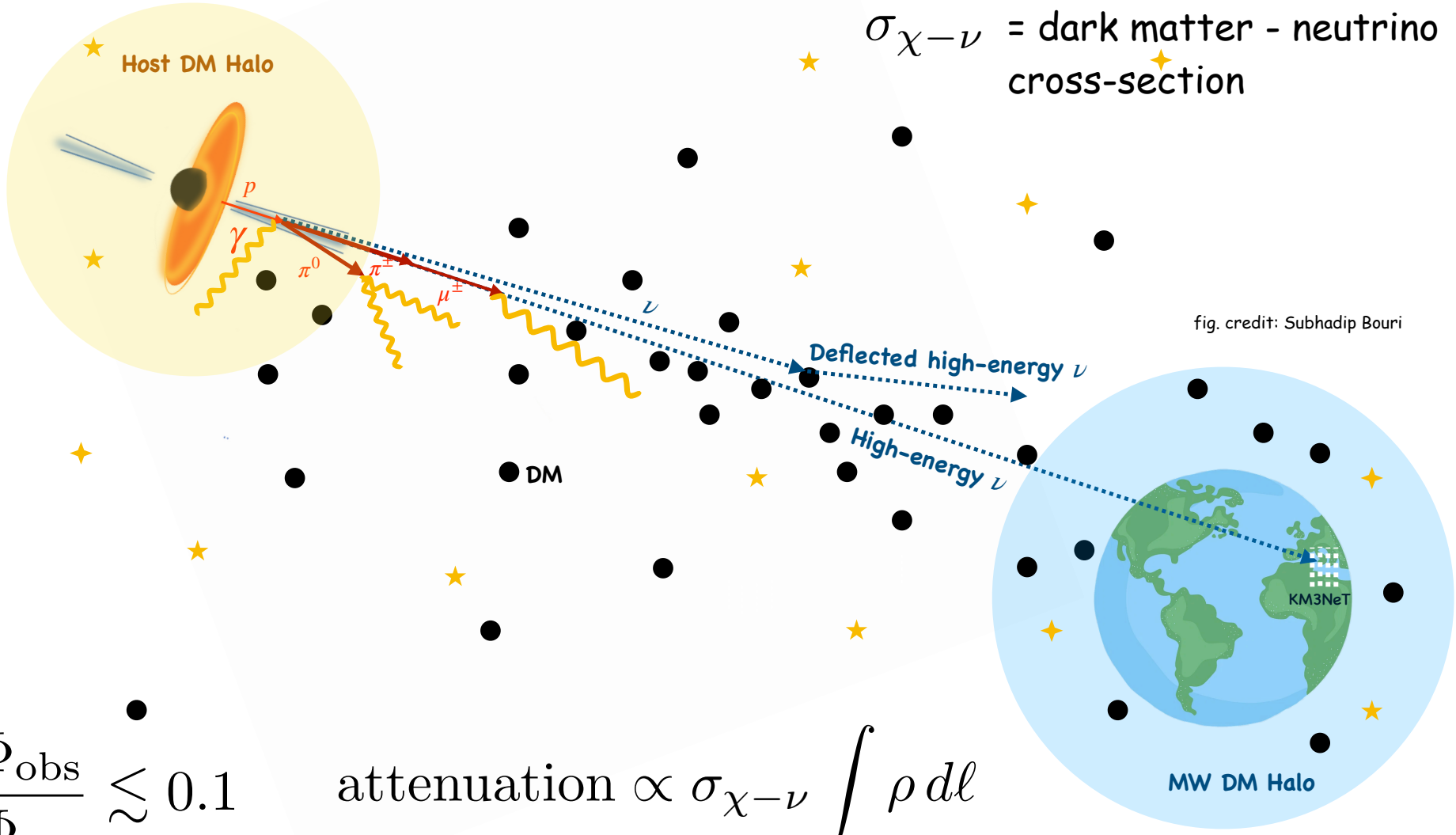
KM3-230213A: beyond the Standard Model physics in propagation?

Given that this is the highest energy neutrino ever detected, it is tempting to think of how we can probe beyond the Standard Model physics with it

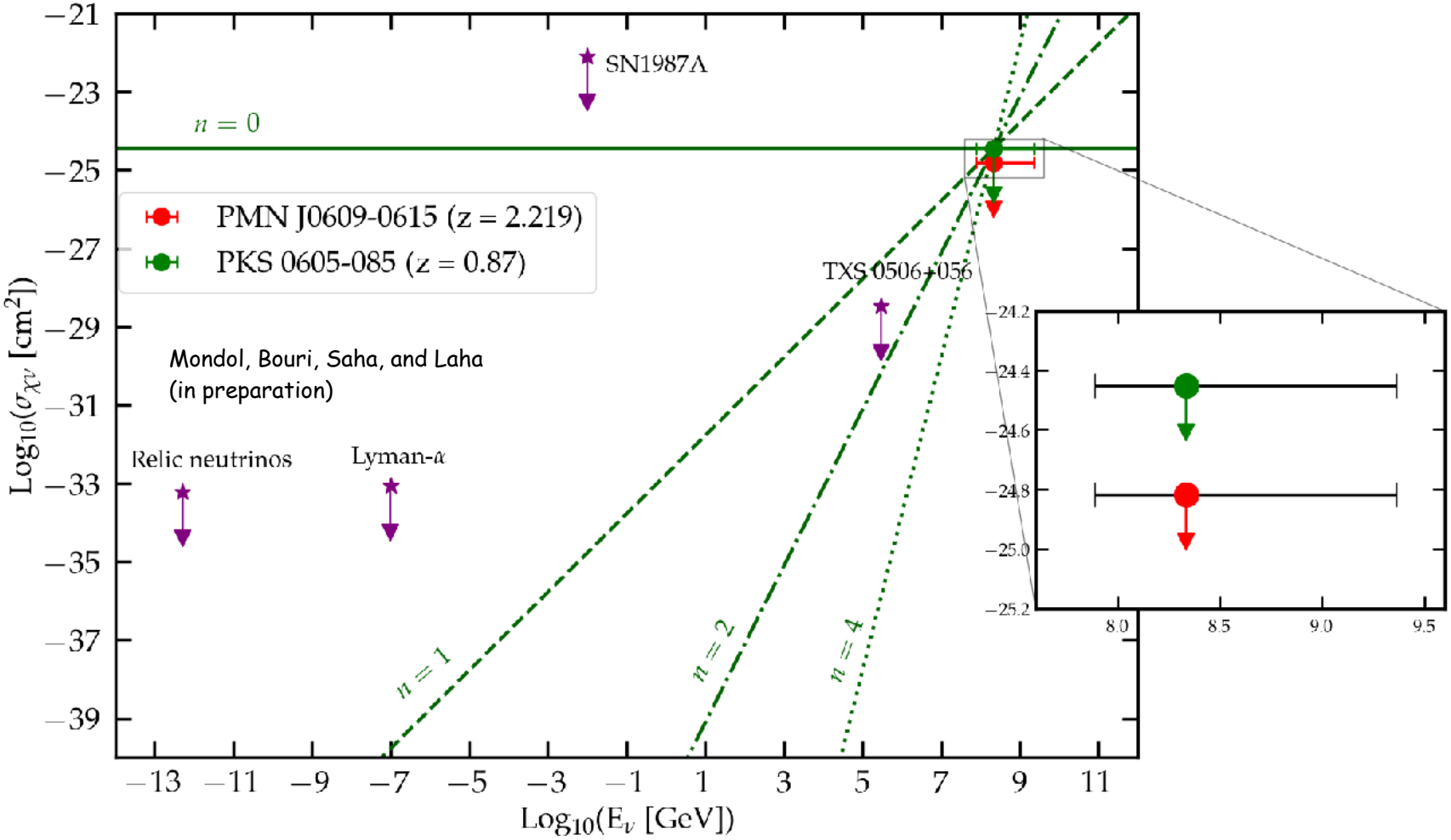
The mere observation of this event implies that the neutrino did not suffer catastrophic attenuation/ deflection during its propagation

The neutrino propagates through a dark matter background (host halo, intergalactic space, and Milky Way halo), thus, we can constrain dark matter - neutrino scattering from this interaction

KM3-230213A: beyond the Standard Model physics in propagation?



KM3-230213A: limit on dark matter - neutrino interaction



KM3-230213A lets us set strong limits on dark matter - neutrino interaction

This limits can be world-leading if the cross-section is energy dependent

Conclusions

- Neutrino telescopes play a leading role in our understanding of astrophysics
- Searches using neutrinos from the Sun and SN 1987A have lead to a deeper understanding of these objects
- High-energy neutrino astrophysics is playing an important role in understanding the high-energy non-thermal Universe
- The discovery of high-energy astrophysical neutrinos by IceCube has opened up a new avenue to our Universe
- The discovery of the high-energy neutrino event by KM3NeT, dubbed KM3-230213A, is the highest energy neutrino ever detected
- We have shown that this single event will put the most stringent constraint on neutrino - dark matter cross-section

Questions & comments: ranjanlaha@iisc.ac.in